# Field $CO_2$ Monitoring of Rooms with Different Air-Tightness Classes and Ventilation Systems

**Parinee Srisuwan[a] and Jatuwat Varodompun[b]***

*[a, b] Faculty of Architecture and Planning, Thammasat Univeristy, Pathumthani 12121, Thailand*

**Abstract**

This research aims to study the important role of room air-tightness on both the Indoor Air Quality (IAQ) and energy consumption of an air conditioning system. Room air-tightness can be categorized by the air change rate: Loose (ACH > 0.60 $h^{-1}$), Average (ACH = 0.40 - 0.60 $h^{-1}$) and Tight (ACH < 0.40 $h^{-1}$). By operating a make-up outdoor air unit supplying these three spaces in different ways, a calculation method of expected carbon dioxide ($CO_2$) concentration based on occupant density and the time period of occupancy was proposed. The methodology of this study is the real-time monitoring of the $CO_2$ concentration (from respiration) in rooms with three air-tightness ranges. Each room was tested under 2 conditions: with the make-up outdoor air unit turned on or off. The $CO_2$ concentration was compared with both the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard (not exceeding 1,000 ppm) and the theoretical ASHRAE 62.1-2007 calculation using the mass balance method. The results show that using a make-up outdoor air unit will improve indoor air quality but consume a lot of energy due to the high cooling load from the outdoor air. Therefore, it is recommended for Average and Tight rooms only. The make-up outdoor air unit not only helps dilute $CO_2$ but also delays the time period it takes for the $CO_2$ to surpass the 1,000 ppm excess threshold. By contrast, $CO_2$ levels in loose rooms are always lower than the standard and rise very slowly. Thus, the make-up outdoor air unit is less necessary. Besides the room's air-tightness and occupancy density, this study discovered that the IAQ also greatly depends on the time period of occupancy – a dimension which is often overlooked. Based on these results, the outcomes of this study can be used to determine whether a make-up outdoor air unit is necessary for any given room, with reference to the impacts on the building's initial cost and HVAC energy consumption.

* Corresponding author.
*E-mail: vjatuwat@hotmail.com*

**Keywords:** Make-up outdoor air units, Recirculated air, Air Infilltration, Air Change Rate Per Hour: ACH, $CO_2$ concentration

## 1. Introduction

In an air conditioned room, indoor air quality control and energy consumption are key design factors. Normally, an air conditioning system must provide adequate Outdoor Air (OA) for maintaining the optimum carbon dioxide ($CO_2$) level. Low $CO_2$ levels in the outdoor air can dilute the concentrated $CO_2$ level resulting from occupants' respiration; however, the temperature and humidity of the induced OA are usually different from the ideal conditions for indoor comfort which, in turn, increase the cooling/heating load for an air conditioning system and raise energy consumption. Consequently, conditioned OA is a major consideration of sustainable design and climate change mitigation.

The cooling load of an air conditioning system does not only come from the outdoor air alone, but also from air infiltration through cracks and leakages. Both account for 36% of the total cooling load, which is sometimes higher than the cooling load from other sources such as envelopes and appliances (McIlvaine et al., 2000). This issue was a central concern during the energy crisis in 1974. As a result, buildings were forced to improve their energy efficiency: one of the key measures to achieve this is to seal the leakage and reduce the ventilation rate. However, the side effect of these practices is a significantly poorer IAQ (Indoor Air Quality). Data shows that 75% of occupants are suffering from asthma and sick building syndrome caused by poor IAQ (FMI, 2002).

Normally, the negative impacts on occupants' health from poor IAQ are caused by air contaminants. These air contaminants, which directly affect the respiratory system, can be classified into many types such as organic compounds, microorganisms, particles and gases. Large-size contaminants can be filtered by effective filters such HEPA. However, small-size contaminants such as gases and vapors cannot be easily filtered and require other methods such as dilution to reduce their concentration. Particularly, carbon dioxide ($CO_2$), which is generated from respiration, is the most important gas to be maintained within an acceptable range. Once the $CO_2$ level surpasses the threshold, many negative symptoms can be found. If occupants continuously inhale air with $CO_2$ levels higher than 1,500 ppm (parts per million), they will suffer from headache, dizziness, squeamish, difficulties concentrating, etc. Since $CO_2$ is one of the most common pollutants of any occupied space, the American Society of Heating, Refrigeration, and Air Conditioning Engineering (ASHRAE) does not only reference $CO_2$ as a baseline for determining adequate OA ventilation rate, but also sets the threshold of $CO_2$ concentration not to exceed 1,000 ppm or 700 ppm above the outdoor $CO_2$ level (American Society of Heating. Refrigeration and Air Conditioning Engineering [ASHRAE], 2007).

At present, the indoor $CO_2$ concentration of particular rooms in a building can be only reduced by outdoor air from both ventilation and infiltration. Ventilation can be controlled using the mechanism of an air conditioning system, fan, and make-up OA unit, while infiltration depends on the air-tightness of the rooms. When the building is sealed and tight, ventilation can be controlled to optimize both energy use and IAQ. On the other hand, if the room leaks, the ventilation control can be less effective. Uncontrolled air infiltration can increase the cooling/heating load while also decreasing $CO_2$ levels unnecessarily lower than the standard. In Thailand, where the cooling load is a major factor of energy consumption, the effects of both ventilation induced through the ventilation system and infiltration through different air-tightness classes are usually overlooked. This research aims to study the interaction between ventilation through a make-up outdoor air unit and infiltration for three levels of room tightness: loose, average, and tight. The impact of both $CO_2$ levels and energy demand will be analyzed to develop parameters to guide ventilation system design. The applications extend toward both new and existing buildings to ensure air conditioning systems provide both energy efficiency and acceptable IAQ for the building occupants.

## 2. Field experiment set-up and research methodology

Field $CO_2$ measurement was conducted in different rooms with varying air-tightness and occupant density. The monitoring activity was set up at the Faculty of Architecture and Planning, Thammasat University (APTU) (Figure 1). Since the location of the testing site is in Thailand, which is hot and humid all year round, the cooling load is the main concern.

### *2.1 Room air-tightness categories*

To categorize the room air-tightness, the crack length calculation method shown in equation 1 was applied (Department of Alternative Energy Development and Efficiency, 2007). $AL_{avg}$ is the average air infiltration rate (L/s), which can be determined using $CL_i$ (crack length of window or door no. *i* (m.)) and $AL_i$ (air infiltration rate of window or door no. *i* (L/s•m)).

$$AL_{avg} = \frac{\sum_{i=1}^{n} CL_i \times AL_i}{\sum_{i=1}^{n} CL_i} \quad [1]$$

**Figure 1.** Faculty of Architecture and Planning, Thammasat University (APTU).

The Average Change per Hour or ACH ($h^{-1}$) shown in equation 2 (ASHRAE, 2005) is commonly used by designers to determine the air volume of a given room being replaced in one hour. ACH can be determined by $Q_i$ or air change rate (L/s) divided by $V$ or volume (L). If there is no ventilation involved, $AL_{avg}$ can be used as $Q_i$.

$$ACH = \frac{3.6Q_i}{V} \qquad [2]$$

The room's ACH can be used to categorize its air-tightness based on CIBSE (Chartered Institution of Building Services Engineers) standard (CIBSE, 2006). An average room with moderate leakage has an ACH between 0.4-0.60 $h^{-1}$. The ACH of a tight room is below 0.4 $h^{-1}$, while the ACH of a loose room is higher than 0.6 $h^{-1}$. Figure 2 shows rooms in APTU with air infiltration rates of ACH 0.31-1.54. With this wide range of ACH, the selected rooms can represent tight, average, and loose constructions for the $CO_2$ measurement to take place.

### *2.2 Field carbon dioxide monitoring*

The experimental set-up refers to ASHRAE standard 55 (2004a). The $CO_2$ measurement device (Testo 435 with $CO_2$ probe) is placed in the center of the room at the breathing

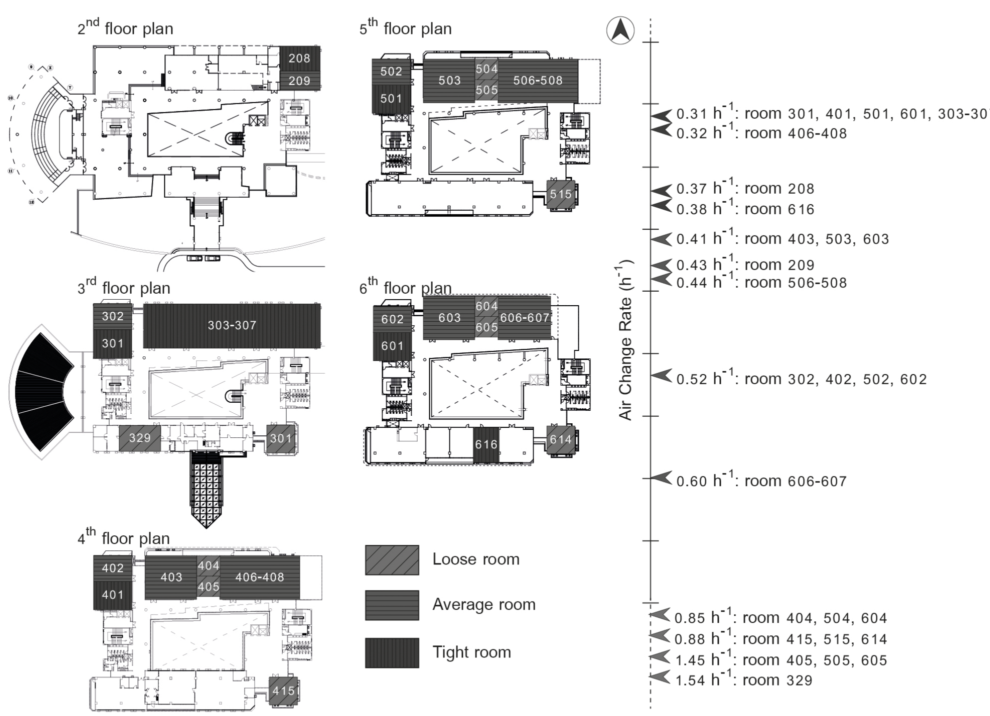



**Figure 2.** Air-tightness classes of rooms in APTU facility.

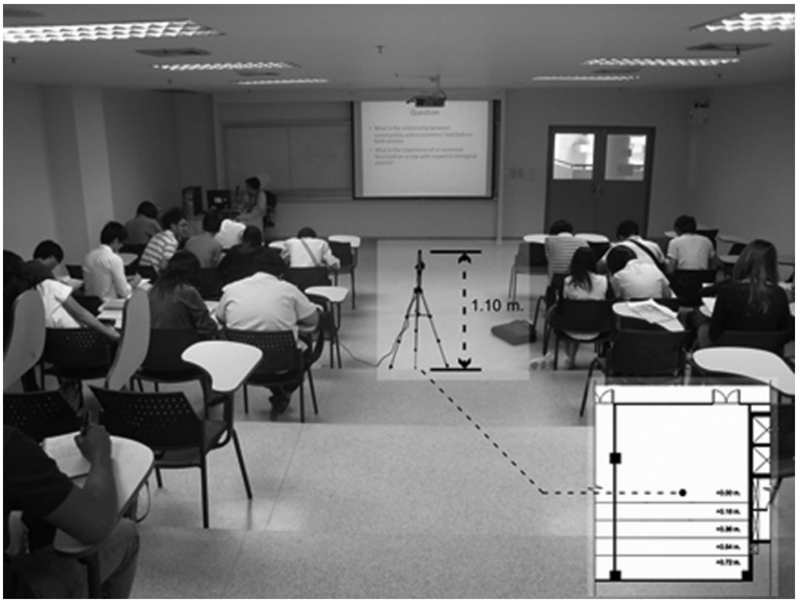



**Figure 3.** The placement of the $CO_2$ monitoring device.

zone (1.1 m. above floor) (Figure 3). The data was recorded at 15 minute intervals. During the measurement, the air conditioning system was turned on, while the other variables including the number of occupants and the frequency of the door being opened were recorded. To study the impact of ventilation, the $CO_2$ levels were recorded when the make-up outdoor air unit was turned both on and off.

The recorded results were compared to three thresholds, including the ASHRAE recommended threshold of 1000 ppm, the theoretical calculation of $CO_2$ levels based on ASHRAE standard 62.1 (equation 3) (ASHRAE, 2004b, 2007), and the $CO_2$ mass balance method (equation 3).

$$C_R = C_{OA} + \frac{8400 E_Z m}{R_P + \frac{R_a A_Z}{P_Z}} \qquad [3]$$

Where $C_R$ is the $CO_2$ concentration measured within the breathing zone (ppm), $C_{OA}$ the $CO_2$ concentration of the outdoor air (ppm), 8400 the human exhalation rate (0.0084 cfm/met/person), $E_Z$ the zone air distribution effectiveness, $m$ the human activity level, $R_P$ the occupancy ventilation rate component (L/s•person) (Table 6-1, p. 13, ASHRAE 62.1-2007), $R_a$ the area ventilation rate component (L/s•$m^2$) (Table 6-1, p.13, ASHRAE 62.1-2007), $A_Z$ the room area ($m^2$) and $P_Z$ the number of occupants (persons).

The theoretical $CO_2$ calculation method assumes that the room conditions remains in a steady state. But in fact, the $CO_2$ levels are mostly transient due to an inconsistent number of occupants and the time period of occupancy. Unlike the theoretical steady state calculation, the mass balance method takes both the number of occupants and the time period of occupancy into account. Equation 4 and Figure 4 represent the mass balance calculation when the ventilation system (a make-up outdoor air unit) is off. Equation 5 and Figure 5 represent the $eCO_2$ calculation when the ventilation system is on.

Where $C_{R(n)}$ is the $CO_2$ concentration of a given space (ppm), $C_{R(n-1)}$ the initial $CO_2$ concentration (ppm), $V_R$ the room volume ($ft^3$) and $V_{RA}$ the volume of air ventilation when the make-up air unit is turned off (cfm). $T_{min}$ is

$$C_{R(n)} = \frac{(C_{R(n-1)} x V_R) + (C_{R(n-1)} x V_{RA} x T_{min}) + (C_{OA} x V_{AI} x T_{min}) + (C_{HE} x V_{MV} x T_{min} x P_Z)}{V_R + (V_{RA} x T_{min}) + (V_{AI} x T_{min}) + (V_{MV} x T_{min} x P_Z)} \qquad [4]$$

$$C_{R(n)} = \frac{(C_{R(n-1)} x V_R) + (C_{R(n-1)} x V_{RA} x T_{min}) + (C_{OA} x V_{MA} x T_{min}) + (C_{OA} x V_{AI} x T_{min}) + (C_{HE} x V_{MV} x T_{min} x P_Z)}{V_R + (V_{RA} x T_{min}) + (V_{MA} x T_{min}) + (V_{AI} x T_{min}) + (V_{MV} x T_{min} x P_Z)} \qquad [5]$$

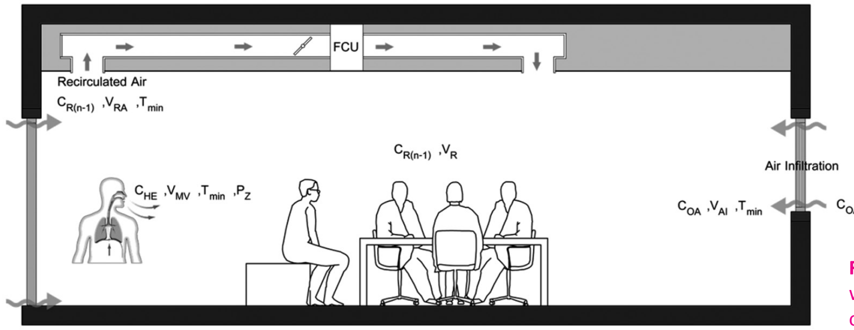



**Figure 4.** $CO_2$ levels in a room when the make-up air is turned off.

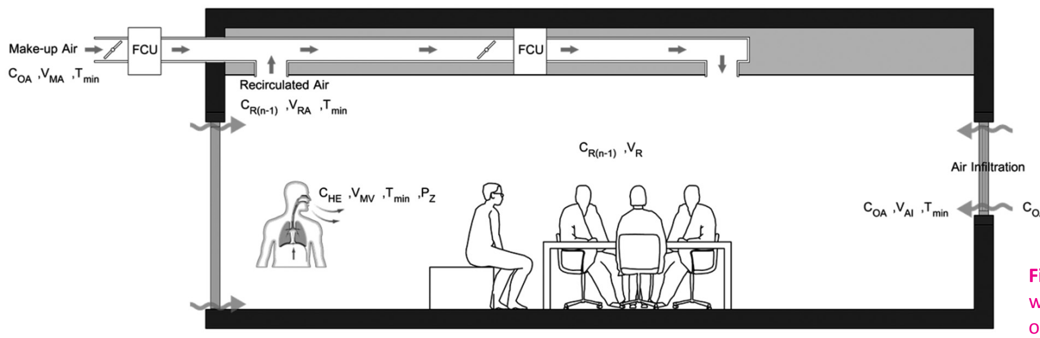



**Figure 5.** $CO_2$ levels in a room when the make-up air is turned on.

the time period of occupancy (min), $C_{OA}$ the $CO_2$ concentration of outdoor air (ppm), $V_{MA}$ the volume of air ventilation supplied by a make-up air unit (cfm), $V_{AI}$ the rate of infiltration (cfm), $C_{HE}$ the $CO_2$ concentration from respiration system (used 41,666 ppm for light activity), $V_{MV}$ the rate of respiration of an occupant (0.212 cfm approximately), and $P_Z$ the number of occupants (persons).

## 3. Field monitoring and numerical results

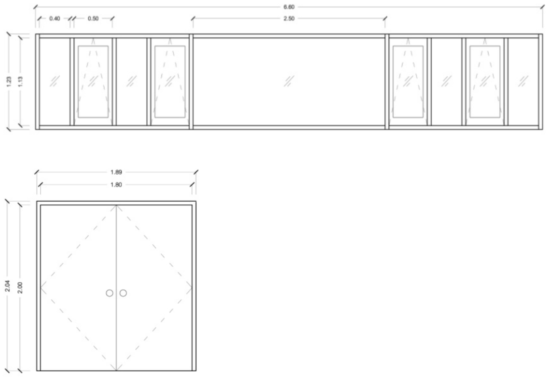
### *3.1 Room air-tightness class and occupancy characteristics*

Using the crack-length method (equation 1), the air infiltration rate of selected rooms can be determined as shown in Table 1. Based on the ACH, the air-tightness class of the rooms in the APTU building can be grouped as loose, average, and tight (Figure 2).

The factors that determine the air-tightness class are the crack-length and room volume. Rooms with long crack lines (joints) and openings tend to promote air infiltration and, in turn, increase ACH. Loose rooms obviously have long crack lines and joints, while tight rooms have fewer windows and openings. A large room requires a longer time period to replace the whole volume; thus, it tends to have a low ACH and makes the rooms tighter. A small room volume does the opposite.

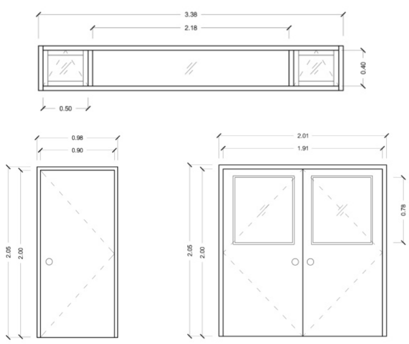
After using the crack-length method, the rooms of the APTU building can be categorized as shown in Figure 2.The loose rooms with ACH > 0.60 $h^{-1}$ are the classrooms (Room 301, 404, 405, 415, 504, 505, 515, 604, 605 and 614) in the east wing and offices (Room 329) in the west wing. The average rooms with ACH 0.40 - 0.60 $h^{-1}$ are the classrooms (Room 302, 402, 502, and 602) in the west wing and computer rooms (Room 209) in the east wing, as well as the studios (Room 403, 406-408, 503, 506-508, 603, and 606-600) in the north wing. The tight rooms with ACH < 0.40 $h^{-1}$ are the classrooms and the computer rooms (Room 301, 401, 501, and 601) in the west wing, the offices (Room 616) in the south wing, and the studios (Room 303-307) in the north zone. The measurement took place during the normal operational hours of the

**Class room (East) i.e. room 415, 515, 614**



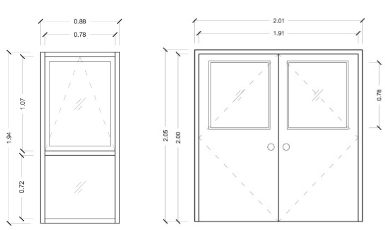
| | |
|---|---|
| **Windows** | Avg. air infiltration rate 0.49 L/s•m<br>Crack length 65.08 m. |
| **Doors** | Avg. air infiltration rate 1.93 L/s•m<br>Crack length 9.60 m. |
| **Total** | Air infiltration rate 50.42 L/s<br>Room’s volume 205.46 $m^3$<br>ACH 0.88 $h^{-1}$ **“Loose room”** |

**Class room (West) i.e. room 302, 402, 502, 602**



| | |
|---|---|
| **Windows** | Avg. air infiltration rate 0.49 L/s•m<br>Crack length 8.76 m. |
| **Doors** | Avg. air infiltration rate 1.93 L/s•m<br>Crack length 5.80 m.<br>Avg. air infiltration rate 1.35 L/s•m<br>Crack length 15.70 m. |
| **Total** | Air infiltration rate 36.68 L/s<br>Room’s volume 254.24 $m^3$<br>ACH 0.52 $h^{-1}$ **“Average room”** |

**Class room (West) i.e. room 301, 401, 501, 601**



| | |
|---|---|
| **Windows** | Avg. air infiltration rate 0.54 L/s•m<br>Crack length 6.70 m. |
| **Doors** | Avg. air infiltration rate 1.35 L/s•m<br>Crack length 15.70 m. |
| **Total** | Air infiltration rate 24.81 L/s<br>Room’s volume 285.26 $m^3$<br>ACH 0.31 $h^{-1}$ **“Tight room”** |

**Table 1.** Example of air infiltration calculation of selected rooms.

school. The researchers placed the recording devices and logged the number of occupants and the door opening frequency hourly. The measurement took place continuously from the beginning to the end of each usage and occupancy. Thus, the time period of the occupancy varied from 3-8 hours depending on the room’s functions. Classrooms and computer rooms tended to have approximately 3 hours of operation, while studios had longer periods of operation (3-5 hours). The longest period of operation (8 hours) was the office.

### *3.2 Monitored and calculated $CO_2$ data*

The following are the time series data of the $CO_2$ levels of three air-tightness classes. Also, the $CO_2$ profiles for the make-up outdoor air units turned both on and off are presented.

### *3.2.1 $CO_2$ levels of the loose rooms (Figures 6 to 8)*

The monitored data and the projections from the mass balance method are almost identical. A discrepancy of only 200-300 ppm was found. The $CO_2$ levels gradually increased from 500 ppm to 1,000 ppm when the class was over. Even though outdoor air was not provided, the $CO_2$ levels never surpassed the 1,000 ppm threshold. On the contrary, the $CO_2$ predictions using the ASHRAE steady state calculation are much higher than the monitored data, reaching 2,500 ppm - a deviation from the monitored data of 1,500-2,000 ppm.

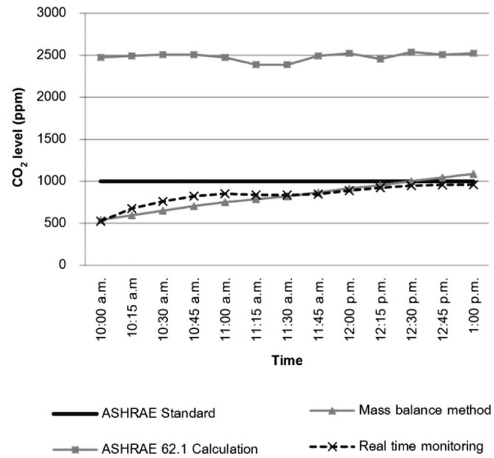



**Figure 6.** $CO_2$ level in a classroom (loose) with the make-up air unit turned off.

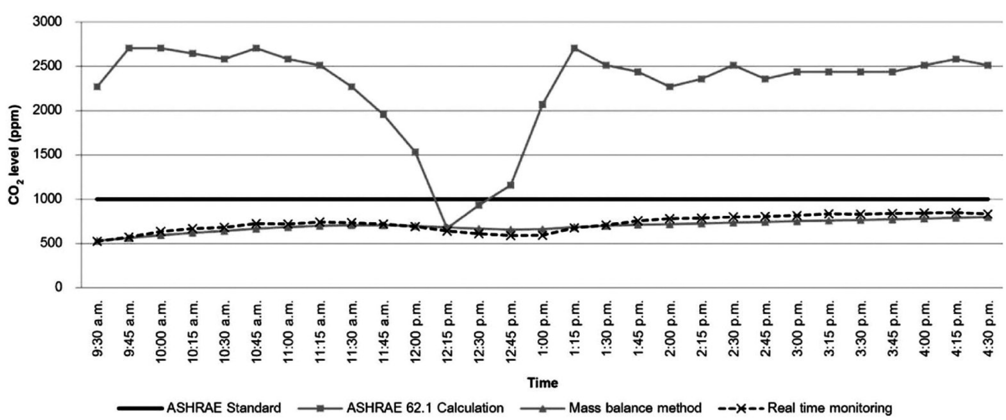



**Figure 7.** $CO_2$ levels in the office (loose) with make-up air unit turned off.

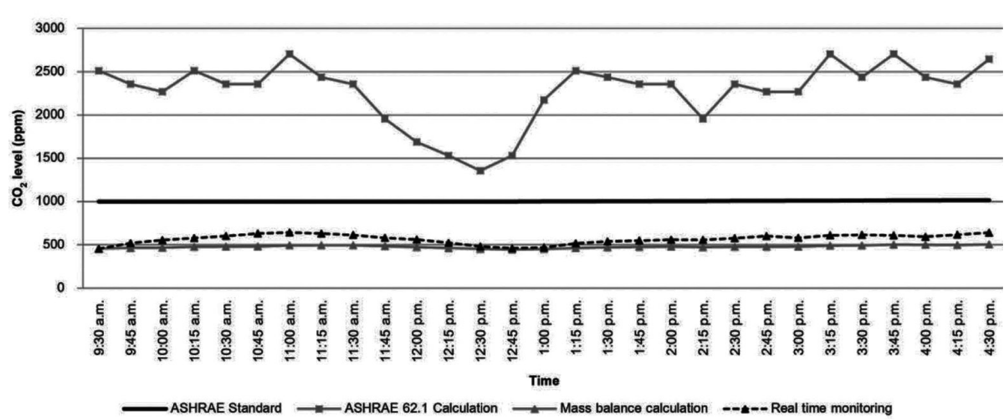
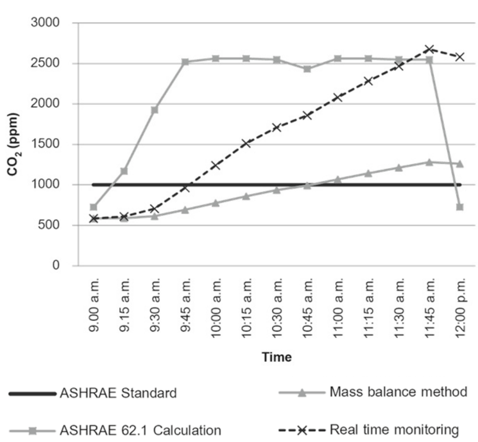
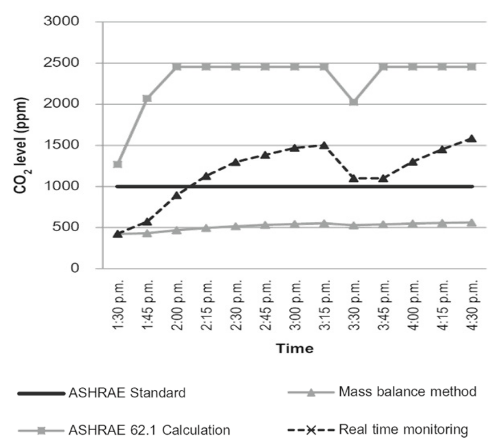



**Figure 8.** $CO_2$ levels in the office (loose) with make-up air unit turned on.

### *3.2.2 $CO_2$ levels of average rooms (Figures 9 to 12)*

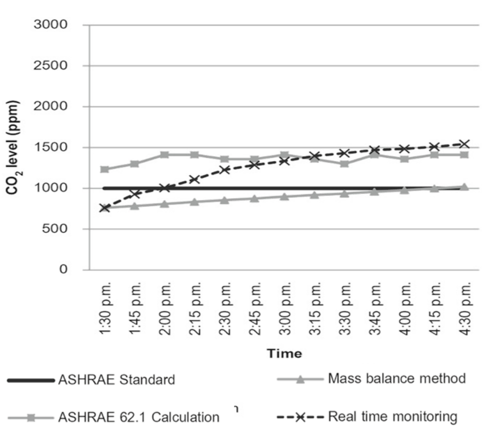
Monitored $CO_2$ levels in the average rooms rose more quickly than those of the loose rooms by a significant degree. The outdoor air from the make-up outdoor air unit clearly slows down the rise in $CO_2$. When the outdoor air was not supplied, the $CO_2$ level surpassed the $CO_2$ 1000 ppm threshold 15 minutes after the occupancy. The supplied outdoor air extends the surpassing time to 45 minutes. In addition, the peak $CO_2$ of the average classrooms with supplied outdoor air is lower, at 1,500 ppm, while the peak $CO_2$ of the rooms without outdoor air is 2,700 ppm (Figures 9 and 10). In addition to the supplied outdoor air, the density of occupants plays an important role in alternating the $CO_2$ accumulation rate. Figures 11 and 12 show the profiles of recorded $CO_2$ of the less dense spaces of the computer rooms and the studios, respectively. The peak $CO_2$ of both rooms is less than that of the classrooms.

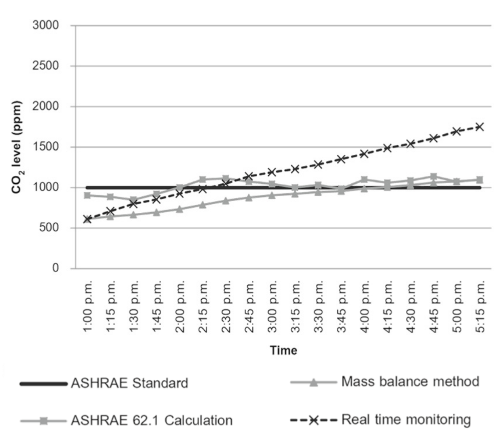



(Left) **Figure 9.** $CO_2$ level in the classroom (average) with make-up air unit turned off.

(Right) **Figure 10.** $CO_2$ level in the classroom (average) with make-up air unit turned on.




(Left) **Figure 11.** $CO_2$ level of the computer room (average) with make-up air unit turned off.

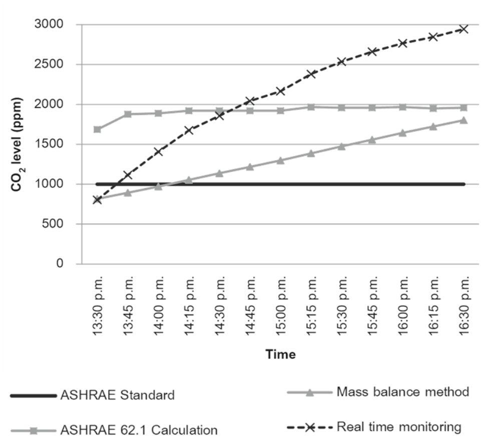
(Right) **Figure 12.** $CO_2$ level of the studio (average) with make-up air unit turned off.

Similar to the loose rooms, the ASHRAE steady state calculation is higher than the recorded data. The mass balance method predicts lower $CO_2$ levels than the recorded data. However, the $CO_2$ profile of the mass balance method fits the field data better. The $CO_2$ level gradually rises as the occupancy period progress.

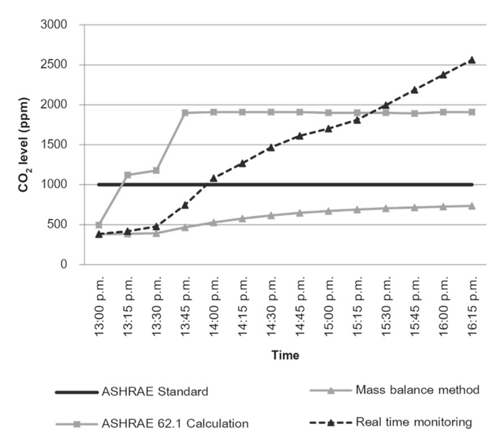
### *3.2.3 $CO_2$ level of the tight rooms (Figures 13 to 17)*

Similar to the average rooms, the $CO_2$ levels of the tight rooms rose quickly along with the extended occupying period. The rooms with dense occupancy, including the classrooms and computer rooms, have much higher $CO_2$ levels than the rooms with lower occupant densities (the office and studio). In the high density rooms, $CO_2$ levels can rise beyond 1000 ppm in as short a period as 15 minutes for the computer room and 30 minutes for the classroom. When the make-up outdoor air unit was operated, the $CO_2$ levels remained below 1,000 ppm for longer.

The $CO_2$ of both the classroom and computer room remained under the threshold for one hour (Figures 13 and 14). For the less dense rooms, the $CO_2$ levels of the office and the studio can be maintained under the threshold for almost the entire occupied period. For the studio, the $CO_2$ levels are lower than the threshold for 2 hours. When the make-up outdoor air is on, the $CO_2$ level of the office is significantly lower than 1,000 ppm (Figures 15, 16 and 17). The $CO_2$ prediction using the mass balance method once again is superior to the ASHRAE 62 calculation method. Although it cannot perfectly predict the $CO_2$ level, its profile still rises and falls along with the monitored $CO_2$ data.




(Left) **Figure 13.** $CO_2$ levels in the computer room (tight) with make-up air unit turned off.




(Right) **Figure 14.** $CO_2$ levels in the computer room (tight) with make-up air unit turned on.

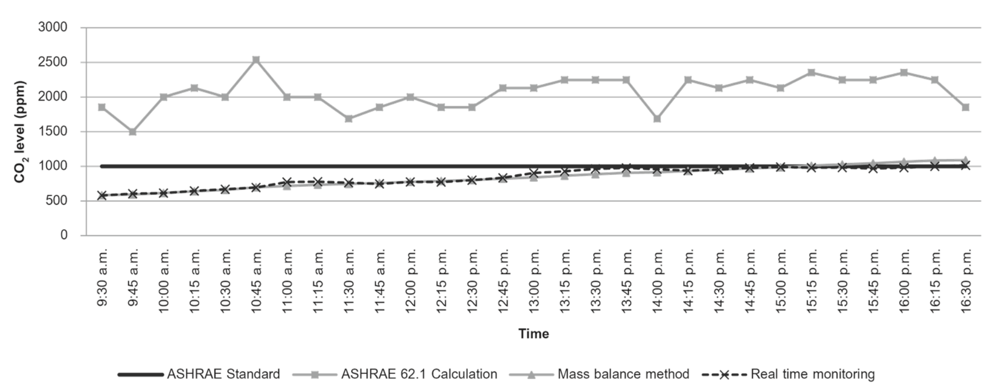



**Figure 15.** $CO_2$ level in the office (tight) with make-up air unit turned off.

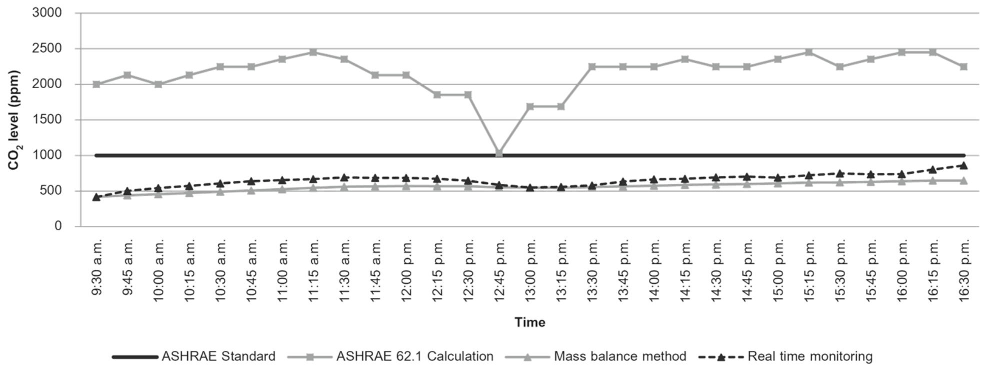



**Figure 16.** $CO_2$ level in the office (tight) with make-up air unit turned on.

## 4. Discussion

### *4.1 Factors impacting on $CO_2$ levels*

Based on the monitored data, the factors which can significantly impact on the $CO_2$ levels will be discussed here. Four factors, including occupant density, door operation, make-up outdoor air unit, and room air-tightness, will be analyzed using the $CO_2$ data shown in Figure 18.

#### *4.1.1 Occupancy density*

The average occupancy density data of the three air-tightness classes are shown in Figure 19. The data shows that the rooms with tight construction also have a higher occupant density, except the average room when the make-up outdoor was operated. These rooms usually indicate a high user density, reaching 0.25 people per $m^2$. Compared to the $CO_2$ data in Figure 18, it is obvious that the $CO_2$ levels rise along with occupancy density. The high density of the average rooms with the make-up OA unit can lead to higher $CO_2$ levels than the average $CO_2$ of the tight rooms. This indicates that occupant density is a key factor that should be considered alongside air-tightness for appropriate ventilation design, particularly for average and tight rooms. The occupant density could raise the $CO_2$ levels beyond the 1,000 ppm threshold if the make-up OA was not turned on. On the other hand, the $CO_2$ levels of both rooms were acceptable when OA was supplied. For the loose rooms, the data presents a different picture. Although the density is lower, the $CO_2$ levels still remain much lower than the standard. There is


**Figure 17.** $CO_2$ level of the studio (tight) with make-up air unit turned off.

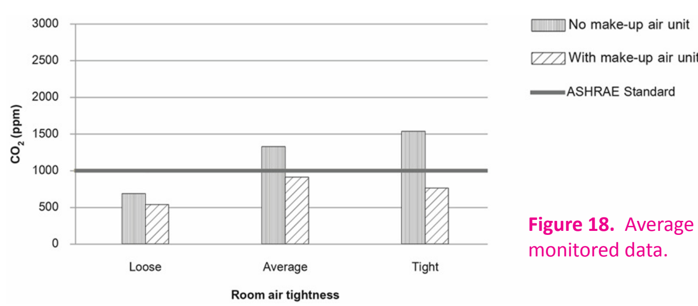



**Figure 18.** Average $CO_2$ levels of monitored data.

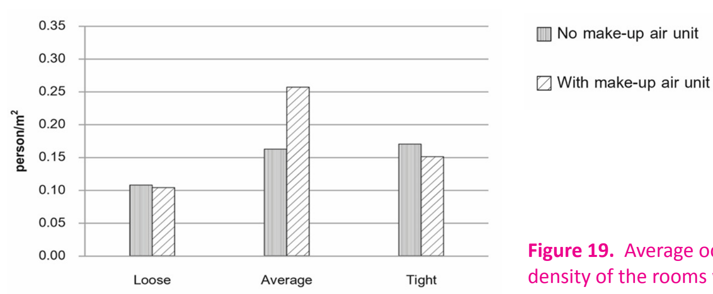



**Figure 19.** Average occupant density of the rooms with 3 air-tightness classes.

room for more occupants, but the $CO_2$ levels still remain acceptable. Thus, if there are less occupants, the make-up OA might not be necessary for the loose rooms.

#### *4.1.2 Door usage*

When the doors open, more air can infiltrate the rooms and, in turn, the $CO_2$ levels reduce. Figure 20 shows the recorded door operation during the monitoring period. In the average and tight rooms, the doors were opened 4-6 times every 15 minutes and the doors were opened less when the make-up OA unit was turned on. Data in Figure 18 shows the $CO_2$ levels of the rooms where only a small number of doors were in use. This indicates that door usage plays a less important role than the direct supply of OA. For the loose room, the door operation with OA units turned both on and off is almost identical, and more frequently opened than the other two rooms. Since the $CO_2$ level of the loose rooms is much lower than the standard, regardless of whether the OA unit was on or off, it appears that leakage plays a more important role in reducing the $CO_2$ levels.

#### *4.1.3 The make-up outdoor air unit*

Based on the data in Figure 18, the make-up OA unit clearly can reduce the $CO_2$ levels of all rooms with different air-tightness classes. It plays a major role in reducing the $CO_2$ levels of average and tight rooms to below the ASHRAE 62 threshold. However, it might not be relevant for loose rooms, since the $CO_2$ is already lower than the standard. This low $CO_2$ level can be achieved even though the make-up OA unit was turned off.

#### *4.1.4 Room air-tightness class*

Results in Figure 18 show that the room air-tightness class can impact on the $CO_2$ level, especially when no make-up OA was in use. $CO_2$ levels significantly increase with the air-tightness of the rooms. When the rooms are sealed and tight, $CO_2$ can easily exceed the 1,000 ppm threshold. In this case, other means such as an outdoor air unit and lower occupant density are necessary. On the other hand, if the rooms are loose and leak, the use of the make-up outdoor air might not be effective. $CO_2$ is already low, but the operation of the make-up OA unit might waste energy on the OA treatment and running the fan.

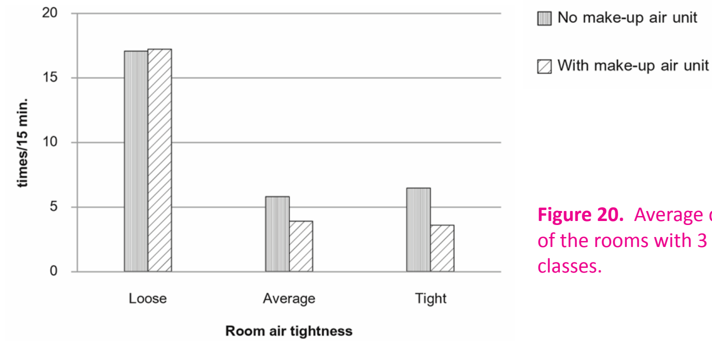



**Figure 20.** Average door usage of the rooms with 3 air-tightness classes.

### *4.2 Monitored and calculated $CO_2$ levels*

To understand the IAQ based on $CO_2$, the monitored data alone is sufficient. However, this study attempts to propose an appropriate model which can at least trend the $CO_2$ levels. Once it is found, the prediction model can be used to create quantitative guidelines for the ventilation design of the different air-tightness class. In this case, two models including the ASHRAE 62 calculations and the mass balance method were tested. In Figures 21 to 23, the average $CO_2$ levels from both methods were compared against the monitored $CO_2$ data. In both the average and tight rooms, the mass balance method tends to underestimate the $CO_2$ levels, while the ASHRAE 62 method overestimates them. For the loose rooms, the ASHRAE calculations considerably over-estimate the $CO_2$ levels, while the mass balance method produces a close prediction.

In addition to the average $CO_2$ data, a closer look at the time series data shown in Figures 6 to 17 reveals more detail. The prediction of ASHRAE 62 does not follow the monitored trends. This model seems suitable only for steady state conditions. But, in fact, the $CO_2$ level of any space accumulates as the occupied period extends. Thus, this method is not appropriate for the prediction of real time

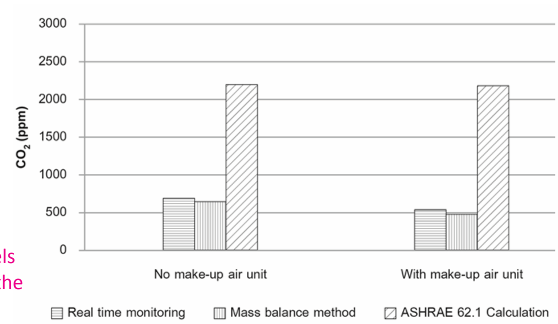



**Figure 21.** Average $CO_2$ levels from different methods of the loose rooms.

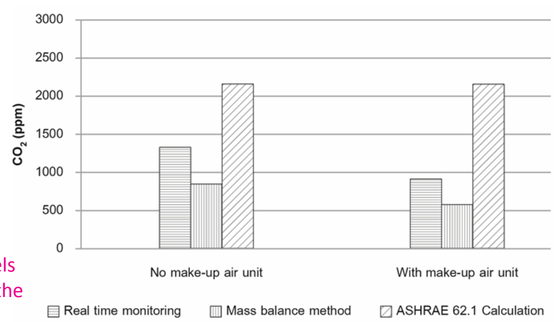



**Figure 22.** Average $CO_2$ levels from different methods of the average rooms.

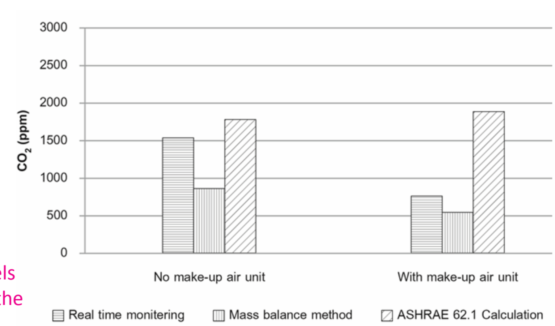



**Figure 23.** Average $CO_2$ levels from different methods of the tight rooms.

data. On the contrary, the mass balance method shows a better prediction rate than ASHRAE 62. Although large discrepancies were found, the predicted $CO_2$ levels rise and fall along with the recorded data. This correlation can be used for predicting $CO_2$ levels using a Regression Model which the analysis and results can be found in the application section. The factors that might affect the predictive accuracy of the mass balance method include:

### *4.2.1 Limitation of the crack-length method*

The air leakage rate of the mass balance method is based on the crack-length method, which is still flawed and inaccurate. The leak rate is assumed to be constant and based on solely the length of the joints and the opening of windows and doors. In reality, the leakage can come from many factors, such as wind and stratification. These factors are sometimes dynamic and capable of significantly varying the $CO_2$ levels. To predict these factors, complex CFD (Computational Fluid Dynamic) analysis might be possible; however, this method also requires extensive validation and may be impractical for implementation. In this study, it was found that the leakage rate might be overestimated for the average and tight rooms. This causes the predicted $CO_2$ level to be lower than the recorded data.

### *4.2.2 $CO_2$ generated by occupants*

The mass balance method assumes that the $CO_2$ generated by occupants is constant. Each occupant generates a $CO_2$ concentration of 41,666 ppm with a constant respiration rate of 0.212 cfm. In fact, age, gender, and activity can greatly vary both the $CO_2$ and respiration rate. Since the absolute value of both variables is almost impossible to obtain, only estimated values can be used. Therefore, the $CO_2$ levels predicted by the mass balance method can be different from the monitored data.

### *4.2.2 Leakage prediction of the door usage*

Although the door operation was recorded, the mass balance method does not include this variable for $CO_2$ prediction. Every time the doors are opened, the air leakage can be very different. The doors might be left open for a long period of time or the wind might blow through the doors in a different way. It is difficult to create a predictive method that includes such impacts. Accordingly, the results predicted by the method can be dissimilar to the recorded data.

## 5. Application

The prediction of $CO_2$ levels in confined spaces can be very useful for ventilation design and practices. Unfortunately, an analytical solution and simple calculation method have yet to be found. The ASHRAE 62 calculation method, which is the most well-known method for ventilation design, seems to be only applicable for the size of the ventilation system based on peak occupancy. This method neglects the fact that $CO_2$ accumulates during the period of occupancy. In contrast, the mass balance method shows a strong correlation with the field monitoring. The scatter plots and regression model between the mass balance method and actual data can be found in Figures 24, 25, and 26 which are for loose, average, and tight rooms, respectively. $R^2$ of 0.4-0.92 indicates correlation between both methods is acceptable.

Another benefit of these regression analyses is the estimation of $CO_2$ levels. Given the initial $CO_2$, the number of occupants, the ventilation and infiltration rates, the $CO_2$ levels according to the mass balance method can be determined. For instance, if the calculations found that the $CO_2$ of the mass balance method is 660 ppm, the expected $CO_2$ levels of the tight room without any ventilation system might be as high as 1000 ppm. In contrast, the users can use this calculation in reverse to find the appropriate density to maintain $CO_2$ levels below 1000 ppm. In this case, the occupant density should not exceed 0.1 person/sqm.

## 6. Conclusions

In this study, the actual $CO_2$ profiles of spaces with different air-tightness classes were presented. In general, $CO_2$ levels will accumulate over time and keep rising as long as the rooms are occupied. The slope of incremental $CO_2$ is justified by the air-tightness class, occupant density, and ventilation system. A leaking space with low occupant density can have very low $CO_2$ levels. If the ventilation system is in use, the $CO_2$ levels of such a space can go even

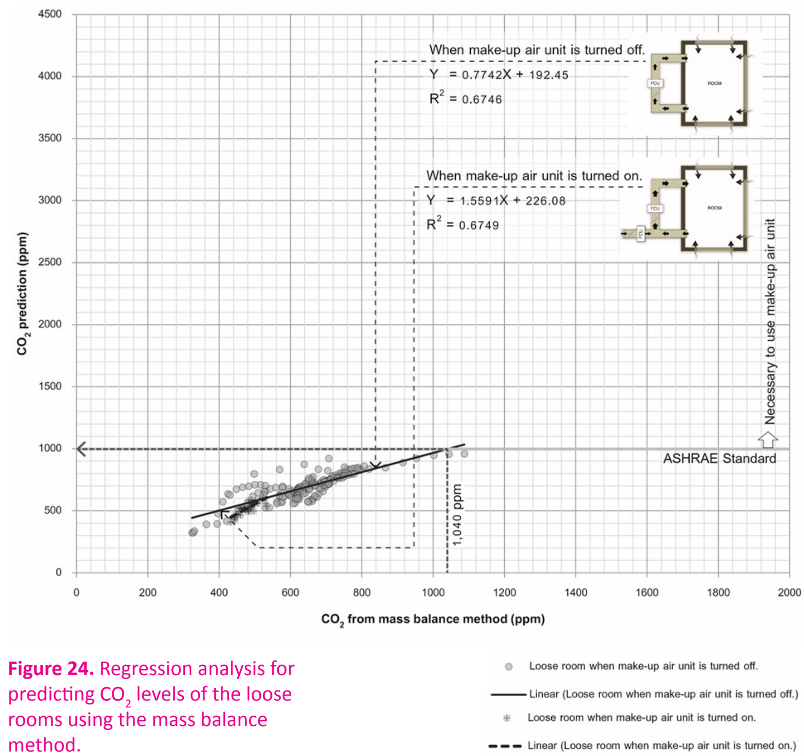



**Figure 24.** Regression analysis for predicting $CO_2$ levels of the loose rooms using the mass balance method.

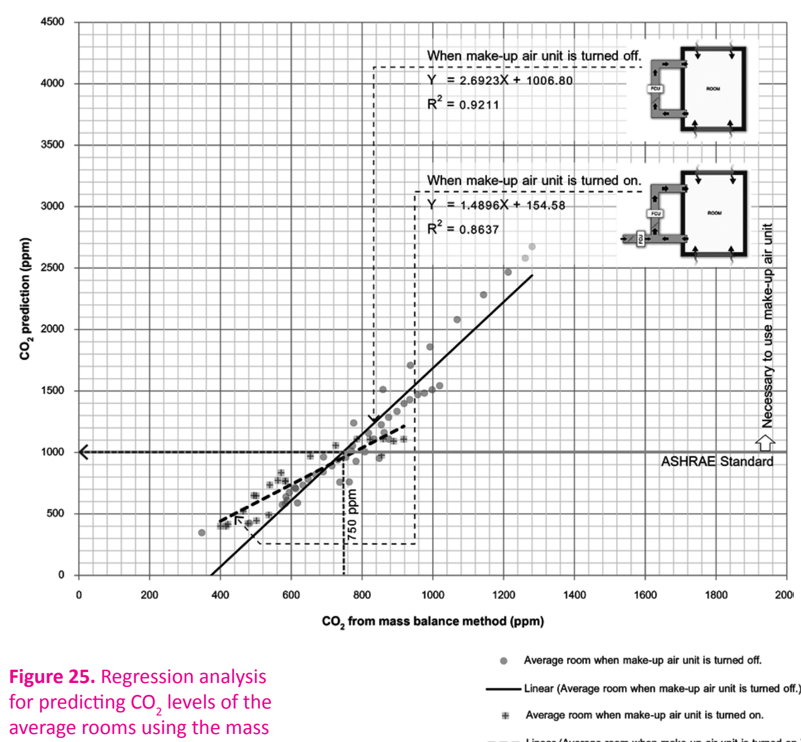



**Figure 25.** Regression analysis for predicting $CO_2$ levels of the average rooms using the mass balance method.

lower. Consequently, energy must be spent conditioning excess OA which, in turn, lowers the building energy efficiency. This gives clear guidelines for designers who may have the chance to design a room with similar characteristics. In any renovation project, equipping a make-up OA unit to a loose room may be the worst case scenario. The best way to design or fix the room is to seal all the leaks and provide a properly sized OA system. To obtain peak efficiency, Demand Controlled Ventilation (DCV) with $CO_2$ sensors to precisely control the $CO_2$ levels is necessary.

However, not all projects have the budget to install a new make-up OA unit and seal all the leakages. In these cases, it would be best if the parameters for justifying the IAQ are provided. Based on the regression analysis presented in the previous section, the predicted occupant density and length of occupancy that still maintains $CO_2$ levels under the 1000 ppm threshold can be determined. Table 2 summarizes the parameters which allow rooms with different air-tightness classes to maintain acceptable IAQ (based on $CO_2$ levels), potentially without having to install make-up OA units or a ventilation system. In this application, $CO_2$ levels can be sustained by air-leakage only. Though this might not comply with the ASHRAE 62 standard, which demands ventilation through a proper distribution system, this application is still useful for many scenarios. For instance, low income leaking houses with an occupant density less than 0.3 person/m$^2$ and an occupied period of less than 7 hours can still provide acceptable IAQ, though no formal ventilation systems are installed. In a third world country context, where formal ventilation systems are a luxury and not available to much of the population, the results can be usefully applied to many building types such as apartments, classrooms, government buildings, houses, and others.

Since this research is based mainly on field data from one specific building only, there is a need for similar research to be conducted in other buildings to increase the sample size and data pool. This would not only increase the validity of this research, but also provide a better understanding of how IAQ parameters work in the actual circumstance, rather than solely in theory. In this study, only $CO_2$, which is the main concern for IAQ in the ASHRAE 62 standard, was focused on. However, future studies should extend to many other substances such as VOC (Volatile Organic Compounds), Microorganisms, Particles, and others.

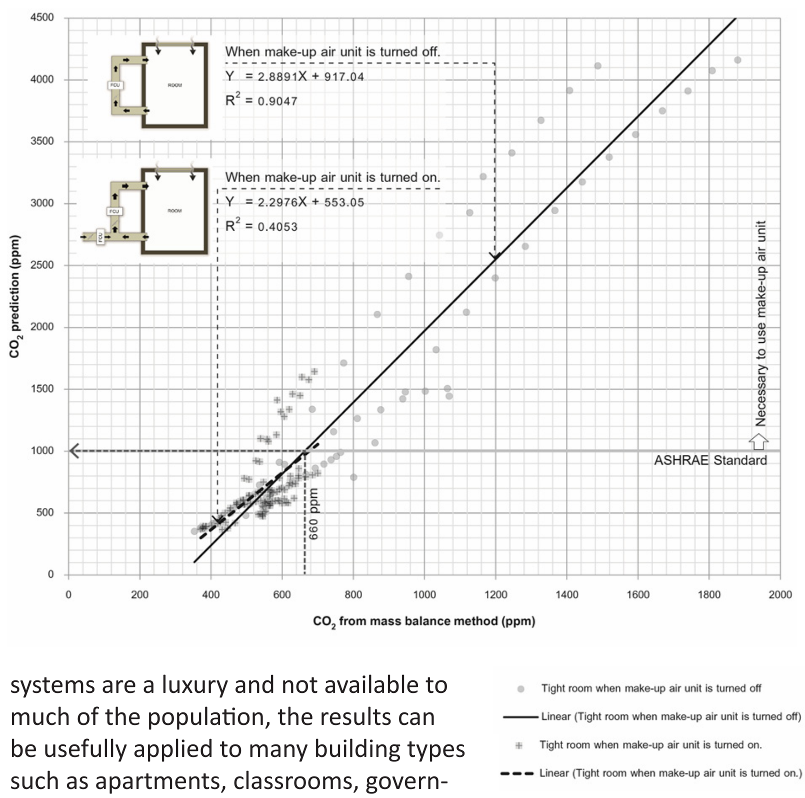



**Figure 26.** Regression analysis for predicting $CO_2$ levels of the tight rooms using the mass balance method.

**Table 2.** The parameters to maintain $CO_2$ levels under the ASHRAE 62 threshold.

| | | Room air-tightness class | | |
|---|---|---|---|---|
| | | **Loose** | **Average** | **Tight** |
| **Factors** | Occupancy density (person/m$^2$) | 0.3 | 0.1 | 0.1 |
| | Time period of occupancy (hr.) | 7 | 1 | 0.5 |

## Acknowledgement

We would like to thank Thammasat University for supporting this research.


## References


American Society of Heating, Refrigeration and Air-Conditioning Engineering. (2004a). Thermal environmental conditions for human occupancy. *ASHRAE Standard 55 - 2004.* Atlanta, GA: Author.

American Society of Heating, Refrigeration and Air-Conditioning Engineering. (2004b). Ventilation for acceptable indoor air quality. *ASHRAE Standard 62.1 - 2004*. Atlanta, GA: Author, quoted in Taylor, S.T. (2006). Demand-controlled Ventilation: $CO_2$-based DCV using 62.1-2004. ASHRAE Journal, 48, pp. 67-75.

American Society of Heating, Refrigeration and Air-Conditioning Engineering. (2005). *ASHRAE Handbook fundamentals (SI ed.), Residential cooling and heating load calculations.* Atlanta, GA: Author.

American Society of Heating, Refrigeration and Air-Conditioning Engineering. (2007). Ventilation for acceptable indoor air quality. *ASHRAE Standard 62.1 - 2007.* Atlanta, GA: Author.

Chartered Institution of Building Services Engineers. (2006). *Maximum Average Air Infiltration Rates in Air Changes per Hour.* Retrieved November 11, 2010, from http://www.arca53.dsl.pipex.com/index_files/tt6.htm

Department of Alternative Energy Development and Efficiency. (2007). *The manual of energy conservation and environmental friendly assessment for non-residential building.* Bangkok, Thailand: Chulalongkorn University Press.

McIlvaine, J., Mallette, M., Parker, D., Callahan, M., Lapujade, P., Floyd, D., Schrum, L., Stedman, T., Cumming, B., Maxwell, L., & Salamon, M. (2000). *Energy efficient design for Florida Educational Facilities.* Retrieved May 17, 2010, from http://www.fsec.ucf.edu/en/publications/html/FSEC-CR-1682-00/images/e-dsn-2.htm

FMI. (2002). *NEM1: Indoor air quality (IAQ) market research.* Retrieved November 22, 2010, from http://www.phocatox.com/pdf/resources/NEMI.pdf